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Identifying conservation priorities for plant species in the Himalaya in current and future climates: A case study from Sikkim Himalaya, India

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ABSTRACT

In recent years, scientific investigations on the effectiveness of Protected Areas (PAs) in conserving biodiversity and sustaining ecosystem functions under the impact of climate change have increasingly received more attention from researchers and park managers. In this study, we used a combination of species distribution modelling (SDM) and spatial hierarchical systematic conservation planning technique to delineate and prioritize areas for endemic plant species conservation under current and future (2050s, 2070s) climate conditions in Sikkim Himalaya. Data on endemic plant species occurrence were sourced from our already published studies and their potential suitable habitats under current and future climates were modelled using Maximum Entropy (MaxEnt) SDM. The MaxEnt habitat suitability projections of species were used in Zonation software to identify priority conservation areas in Sikkim Himalaya. We found that the existing PA network in the region was inadequate in conserving the endemic plant diversity either in the current or future climate scenarios. Based on our results, we propose addition of 896 square kilometres (sq km) to the existing PA network in the study area to ensure meaningful conservation goals. Additionally, we propose creation of 3 new PAs (Yumsedong, Lachen and Chungthang) and the need for expanding the boundaries of existing PAs (Maenam, Fambong Lho and Barsey) in the study area. Our analyses show that to mitigate the effects of ensuing climate change, a single large PA with wide geographic and elevational extents instead of several smaller PAs would be a more prudent strategy for conserving the plant diversity in the Himalaya.

1. Introduction

Protected Areas (PAs) are used world over as a common regulatory and management tool for 'in situ' conservation of natural communities and ecosystems. PA is an area that is legally delimited, managed or recognised for long-term conservation of nature and the associated ecosystem services and cultural values (Dudley, 2008). As of 2016, a total of 202,467 terrestrial PAs exist globally, covering approximately 14.8% of the earth's geographic area (UNEP-WCMC and IUCN, 2016). In India, there are 733 PAs covering 160,901.77 square kilometres (sq km) that amounts to a little < 5% of its geographic area (ENVIS, 2017). Even though PAs are used as an important tool in biodiversity conservation, the debate continues whether PAs conserve biodiversity efficiently (see Curran et al., 2004; Craigie et al., 2010; Chape et al., 2005; Ginsberg, 2017; but see Gaston et al., 2008; Cantú-Salazar and Gaston, 2010; Gray et al., 2016). The efficacy of PAs is also being greatly undermined under the impact of climate change (Hannah et al., 2007). Numerous modelling studies have predicted loss of numerous species from their existing PA reserves due to on-going climate change (Araújo et al., 2004, 2011; Kharouba and Kerr, 2010). Therefore, serious concerns have been expressed about the conservation efficiency of existing PAs under future climate change scenarios (Pressey et al., 2007; Hole et al., 2009; Araújo et al., 2011).

Mountain ecosystems all over the world are considered to be the most fragile and prone to the effects of climate change (Nogués-Bravo et al., 2007; Dobrowski and Parks, 2016; Pandit, 2017). Mountains have reportedly warmed by 0.65 °C during the past five decades at a rate of 0.13 °C/decade (Pepin and Seidel, 2005). As a result of this enhanced rate of warming, species have migrated, adapted or gone extinct in the mountains (Aitken et al., 2008; Telwala et al., 2013; Manish et al., 2016; Pandit, 2017). Climate change presents a bleaker situation for the Himalayan mountain ecosystems. The region has experienced warming at a rate of 0.06 °C/year as compared to the global average of 0.02 °C/year during the past three decades (Shrestha et al., 2012; see also

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Telwala et al., 2013). This unprecedented rate of warming poses serious threat to the survival of the endemic species in the Himalaya (Pandit et al., 2014; Pandit, 2017). In one of our previous studies, we documented likely extinction of 17% and 18% endemic plant species by 2050s and 2070s, respectively due to on-going climate change in the region (Manish et al., 2016). We also reported that the large majority of these endemic plant species had shown a progressive northward shift towards higher elevations in the study area (Telwala et al., 2013; Manish et al., 2016). It is, therefore, necessary to design conservation areas in the Himalaya keeping in mind future climate change scenarios for pragmatic and effective management of the plant biodiversity in the region.

A number of studies have incorporated effects of future climate change scenarios in their systematic conservation planning frameworks (Margules and Pressey, 2000; Leach et al., 2013; Watson et al., 2013). However, to the best of our knowledge, such studies are largely lacking in the Himalaya. Various studies on the impact of climate change on the Himalayan flora have been so far been limited to documenting the changes in phenology, effects on crop productivity, tree line shifts and changes in elevational ranges of species and plant communities (Xu et al., 2009; Dhar, 2012; Singh et al., 2012; Basannagari and Kala, 2013; Telwala et al., 2013; Manish et al., 2016). In this study, we address this critical information gap by designing a PA network in Sikkim Himalaya that is resilient in conserving plant species and their habitats under future climate change scenarios. Specifically, we addressed the following broad questions: (i) Is the existing PA network in Sikkim adequate to conserve plant biodiversity under current and changing climate scenarios? (ii) Are more PAs needed to reduce the vulnerability of plant taxa to changing climate? (iii) Is there a need to re-design conservation boundaries of the existing PAs? (iv) Are larger PAs more effective for conservation than smaller PAs? Sikkim was specifically chosen as a study area to examine these research questions because the concept of PA as a conservation management tool in Sikkim has a long history. The first PA in Sikkim, Khangchendzonga National Park, was established in 1977 followed by Kyongnosla Alpine Wildlife Sanctuary in the same year. Since then, the total number of PAs in the region gradually grew to 8, with the latest (Kitam Wildlife Sanctuary) notified in 2002 (WII, 2017). This makes Sikkim the top Indian state with the highest percentage of its geographical area under PA network (~ 31%).

2. Material and methods

2.1. Study area

The study area is located between 27°00′46″ to 28°07′48″ N latitude and 88°00′58″ to 88°55′25″ E longitude in the Indian state of Sikkim, a constituent province of the Eastern Himalaya (Fig. 1). Sikkim is one of the smallest states of India with a total geographical area of 7096 sq. km and is surrounded by Tibet in the north and northeast, by Darjeeling district of West Bengal in the south, by Chumbi valley of Bhutan in the southeast and by Nepal in the west. The state has a natural elevational gradient from 213 m in the south to above 8000 m in the north and northwest. The region receives an average annual rainfall of about 2534 mm, with July recording maximum rainfall of 480 mm and minimum rainfall of 19 mm in the month of December. The average annual temperature of Sikkim is 18 °C, with minimum temperature of −13 °C or lower in the alpine zones and maximum temperature of 26 °C at lower and mid elevations (CISMHE, 2007).

2.2. Species distribution data

We chose endemic angiosperm species (species endemic to the Eastern Himalaya and occurring in Sikkim) as a proxy for conservation prioritization in the present study because endemic taxa are highly vulnerable to climate change due to their habitat specificity, restricted geographic distribution, small population size and greater sensitivity to variable temperature and precipitation regimes (Malcolm et al., 2006; Bellard et al., 2012). We incorporated data on presence and elevational distribution ranges of 584 endemic angiosperm species based on our already published studies and primary field surveys spread over 121 sampling locations and 625 plots, and also verified from 33 published sources (Fig. S1; Manish et al., 2016, 2017; Manish and Pandit, 2018a). Primary field surveys were carried out along an elevational gradient of 300–5300 m; we used 10 m × 10 m nested quadrats at lower elevations (300–4000 m) and nested Modified Whittaker Plot (MWP) design of 20 m × 50 m at higher elevations (4000–5300 m) (see Manish et al., 2016, 2017;Manish and Pandit, 2018a for full sampling details). The sampling locations of various species were geo-referenced and recorded in terms of latitude and longitude using a hand held GPS system (Magellan TM, SporTrack Map). Once geo-referenced species locations were recorded, their presence was interpolated at every 100 m elevational band in a Digital Elevation Model (DEM) in Arc GIS 9.3 between their recorded minimum and maximum elevations (see Manish et al., 2016).

2.3. Maximum Entropy (MaxEnt) modelling

Potential habitat for each endemic species in the current and future climates (2050s, 2070s) was sourced from our earlier published study (Manish et al., 2016) where we had used MaxEnt ver. 3.3.3 k (Phillips et al., 2006) to model species habitat. MaxEnt models potential habitat of a species by relating its known locations under current climate conditions and then uses this relationship to model potential habitats under future climates (Elith and Leathwick, 2009). Data for different climate scenarios (current, 2050, 2070) were downloaded from the Worldclim database (http://www.worldclim.org/) in the form of 22 environmental variables (monthly average minimum and maximum temperature, monthly total precipitation and 19 bioclimatic variables) at a resolution of 30 arc-seconds (~ 1 km × 1 km grid resolution). Future climate data were based on the IPCC 5th assessment report and four representative concentration pathways (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5), as available from 8 different General Circulation Models (BCC-CSM 1-1, CCSM4, GISS-E2-R, IPSL CM5A LR, Had GEM2-ES, MIROC-ESM-CHEM, MRI-CGCM3, Nor ESM 1M). However, the use of MaxEnt requires input of non-collinear environmental variables. For this purpose, we prepared a correlation matrix using Band Collection Statistics tool in Arc GIS 9.3 and the environmental variables whose correlation coefficient was > 0.6 were excluded in MaxEnt exercise (Manish et al., 2016). The interpolated geo-referenced species locations and non-collinear environmental layers were then used for modelling potential habitat of every endemic species under current climate conditions using the standard calibration settings (see Manish et al., 2016 for details) and the relationship was then used for modelling potential habitat of each endemic species under future climates (2050, 2070) for different emission scenarios (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5). We used Area under Receiver Operating Characteristic curve (AUC) criterion to test the accuracy of every MaxEnt output. We selected only those habitat projections whose AUC scores were > 0.7 (Leach et al., 2013; Manish et al., 2016). The output generated by MaxEnt was in the probability range of 0 to 1 with 0 representing the least suitable habitat and 1 representing the most suitable habitat (Manish et al., 2016). We calculated average probability of each endemic species' occurrence under different climate conditions (current, 2050, 2070) and different emission scenarios in future climates (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) by averaging the habitat projections over the entire range of 8 General Circulation Models. In this manner, we generated a total of 5256 different species habitat projections for 584 endemic species investigated in the study area (see research data linked to this article). These 5256 species habitat projections were then converted into ASCII text files using Arc GIS 9.3 in the form of raw values for each pixel (1 km × 1 km) and used in conservation prioritization exercise.

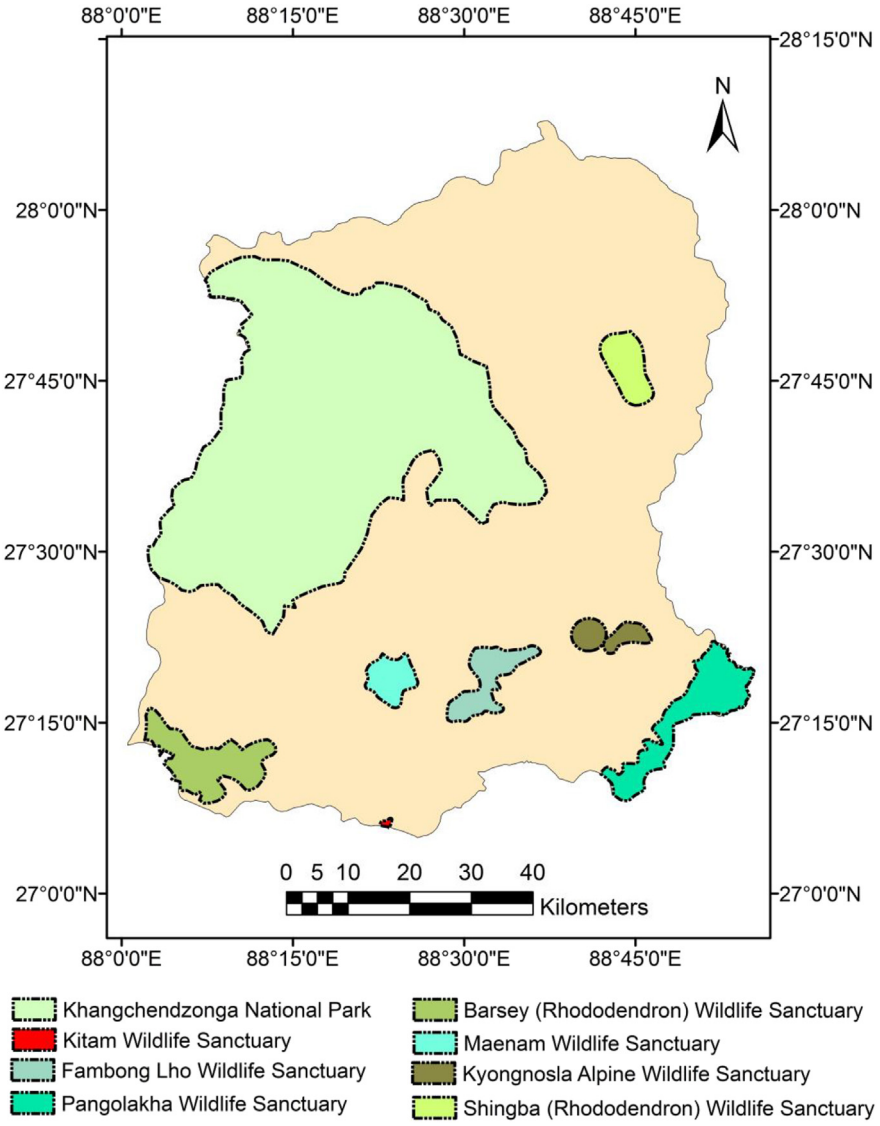


Fig. 1. Location of the study area with existing Protected Areas (PAs) boundaries. PA boundaries were sourced from World Database on Protected Areas (https://protectedplanet.net) and official map of protected areas in Sikkim (http://sbbsikkim.nic.in/sikkim-conservation-pan.html).

2.4. Prioritization of conservation areas

We used Zonation ver. 4.0 (Moilanen et al., 2014) for identifying and prioritizing conservation areas under the current and future climate scenarios and for different emission scenarios (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5 in both 2050 and 2070) in this study. Zonation applies a complementarity-based ranking algorithm to prioritize areas based on the principle of maximal retention of weighted range-size corrected feature richness (Moilanen et al., 2011). It starts with the assumption that in best-case scenario, protecting everything for conservation is ideal and then iteratively ranks cells by removing those whose loss leads to the smallest aggregate marginal biodiversity loss. The output produced by Zonation is a nested one, meaning top 1% of landscape lies within top 2% of landscape which in turn lies within top 5% of landscape, and so on (see Lehtomäki and Moilanen, 2013).

To prioritize and delineate conservation areas in current and future climates, we used the predicted habitat distributions of 584 endemic species in the form of raw values for each pixel (1 km × 1 km) from MaxEnt modelling. Two different runs were performed in Zonation to rank conservation areas: (i) without including existing PA network of the Sikkim Himalaya (Scenario 1), and (ii) including existing PA network of the Sikkim Himalaya (Scenario 2). The difference between the two runs was that the cell ranking was done using normal Zonation hierarchical prioritization process in Scenario 1, while in Scenario 2, Zonation first ranked all the cells outside the PA boundary followed by ranking of the cells inside PA limits. In this way, it was assumed that the highest conservation priority areas in Scenario 2 were covered under the existing PA network. Scenario 1 is thus an ideal case where boundaries of existing PAs would need to be redrawn and new PAs would be designed afresh. However, the results of Scenario 2 are more pragmatic to implement, as it would be easier to expand the already existing PAs network. We delineated the existing PA network in Sikkim Himalaya using the World Database on Protected Areas (https://protectedplanet.net). However, this database included the boundaries and details of only six protected areas in Sikkim Himalaya (Khangchendzonga National Park, Barsey (Rhododendron) Wildlife Sanctuary, Fambong Lho Wildlife Sanctuary, Kyongnosla Alpine Wildlife Sanctuary, Maenam Wildlife Sanctuary and Shingba (Rhododendron) Wildlife Sanctuary). For the remaining two protected areas (Pangolakha Wildlife Sanctuary and Kitam Wildlife Sanctuary), we digitized their boundaries using the official map of the protected areas in Sikkim (http://sbbsikkim.nic.in/sikkim-conservation-pan.html) in Arc GIS 9.3 platform using GCS WGS 1984 projection system (see Fig. 1). Two factors were kept constant throughout the Zonation

runs: warp factor and species weighting. The warp factor (defined as number of cells removed in each iteration step) was taken as 100 in accordance with the standard literature (Leach et al., 2013; Wan et al., 2014; Wang et al., 2016). In all the runs, species weights were determined using the following formula:

$$W = \left(\frac{100}{ER}\right)$$

where, W = weight of each individual species; ER = Elevational range of a species (Maximum elevation of a species – Minimum elevation of a species).

The above formula ensured that species with broad elevational ranges were assigned lower weight than the species with smaller elevational ranges. This step was necessary as the species with small elevational ranges in Sikkim Himalaya are known to have reduced tolerance for wide climate fluctuations and are more likely to go extinct than those with large elevational ranges (see Telwala et al., 2013; Manish et al., 2016).

Further, in Scenarios 1 and 2, two cell removal rules, namely (i) Core-area Zonation (CAZ) rule and (ii) Additive Benefit Function (ABF) rule were used to rank areas within the study area. The cell removal rule determines how the conservation value of different cells (areas) within a landscape is calculated (see Moilanen, 2007). CAZ aims to maintain high quality (conservation value) areas for all species. ABF, on the other hand, defines conservation value of a particular cell as the sum of values of the cells for all the species. We could not chose a priori between the two cell removal rules as both are frequently and collectively used to prioritize conservation areas in different climate conditions (Leach et al., 2013; Lehtomäki and Moilanen, 2013; El-Gabbas et al., 2016). Thus, we combined the results of prioritization ranking based on both cell removal rules in Scenarios 1 and 2 using Weighted Sum Overlay method in Arc GIS 9.3. This step enabled us to achieve the most conservative estimate of prioritized ranking over the entire landscape in the Sikkim Himalayan region. The default rate of loss of conservation value while using ABF was taken as 0.25 (exponent of species-area relationship in the Himalaya; see Pandit et al., 2007; Pandit and Grumbine, 2012) in all the Zonation runs.

The output from Zonation runs were ASCII raster files with ranked conservation values from 0 to 1 for each 1 km × 1 km pixel cells. Values close to 0 in the output indicated areas with least conservation value and close to 1 indicated high priority areas for conservation (Moilanen et al., 2005, 2011). Since we used Weighted Sum Overlay method to combine the results of CAZ and ABF Zonation runs in Scenarios 1 and 2, the final conservation priority rank outputs in these had priority scores ranging from 0 to 2 (0 being the lowest and 2 the highest priority score).

The final conservation priority rank outputs produced following the above steps were imported as ASCII files in Arc GIS 9.3 and mosaicked together using 'Mosaic' sub-tool to analyse if the existing PA network in Sikkim Himalaya adequately conserved optimum number of species under current and future climate conditions. In the mosaicked outputs, we designated cells with weighted Zonation score of > 1.5 as 'highest conservation priority cells'. This selection of top ranked 25% of landscapes for conservation prioritization was assumed to be the most conservative estimate for systematic conservation planning in the study region, and was also in accordance with the recent standard literature (Reside et al., 2017; Verhagen et al., 2017). The top 25% landscape areas were processed in Arc GIS 9.3 and converted into polygon shape files using GCS WGS 1984 projection in order to compute the actual geographic areas of the highest priority conservation areas. We then analysed the percentage of these top 25% landscapes with highest conservation values lying within the existing PA network using the following formula:

$$PO = \left(\frac{A_1}{A_2}\right) \times 100$$

where, PO = Percentage overlap; A_1 = Geographic area (sq. km) of pixel cells with weighted Zonation score > 1.5 within each respective PA; A_2 = Geographic area (sq km) of all pixel cells in the study area with weighted Zonation score of > 1.5.

We also evaluated additional areas, if any, with weighted Zonation score > 1.5 outside the existing PA boundaries and that needed to be delineated as new PAs using simple querying function in Arc GIS 9.3. Geographic area and spatial extents occupied by such potential PAs were also evaluated using 'Spatial Analyst' tool in Arc GIS 9.3.

3. Results

Our endemic species dataset in the current study comprised a total of 584 species belonging to 68 families (see research data linked to this article). Orchidaceae was the most speciose family (67 species) followed by Asteraceae (44 species), Gentianaceae (29 species), Primulaceae (28 species) and Saxifragaceae (20 species). Under the current climate scenario, maximum endemic species were found to show their most preferable habitats at mid and higher elevations in Sikkim Himalaya (2000–4500 m) (see research data linked to this article). In future climates (2050s, 2070s) almost all the species were showed a northward shift from their potential habitats towards higher elevations under all emission scenarios (see research data linked to this article).

The extents of priority conservation areas in the study region varied greatly between Scenario 1 and Scenario 2 under different RCPs and climate conditions (Fig. 2). The results of Scenario 1 indicated that the areas with highest conservation values (Weighted Zonation score > 1.5) were located between 2000 and 4700 m in current climate conditions, between 2100 and 5200 m in 2050s (RCP 2.6 = 2100–5000 m; RCP 4.5 = 2100–5100 m; RCP 6.0 = 2200–5200 m; RCP 8.5 = 2200–5200 m) and between 2100 and 5300 m in 2070s (RCP 2.6 = 2100–5200 m; RCP 4.5 = 2200–5200 m; RCP 6.0 = 2300–5300 m; RCP 8.5 = 2400–5300 m) (Fig. 2). Contrastingly, Scenario 2 results revealed that areas with the highest conservation values (Weighted Zonation score > 1.5) were not continuously distributed along the elevational gradient as in Scenario 1, but were instead localized in specific zones. These highest priority zones include areas such as Yumsedong, Lachen, Chungthang, Khangchendzonga National Park, Maenam Wildlife Sanctuary, Fambong Lho Wildlife Sanctuary, Pangolakha Wildlife Sanctuary and Barsey (Rhododendron) Wildlife Sanctuary (Fig. 2). However, unlike in Scenario 1, there was little variation in Zonation priority scores for different climate conditions during different time periods (current, 2050s and 2070s) and RCPs (Fig. 2). In both Scenario 1 and 2, the results of Zonation runs also varied with the use of CAZ and ABF cell removal values (see Fig. S2). Under CAZ, the highest priority scores were located mostly at high-elevations in both Scenarios 1 and 2 (3900–4500 m), whereas under ABF, the highest conservation priority areas were restricted to mid-elevations (2600–3600 m) (Fig. S2).

When the results of different Zonation runs under various climate conditions were mosaicked together for Scenarios 1 and 2 separately, we found contrasting results. In Scenario 1, a continuous elevational zone from 2200 to 5100 m encompassing a total geographical area of 2156 sq. km would be needed to be set aside as a new PA (Fig. 3). However, Scenario 2 results indicated the need for establishing three additional PAs and expansion of boundaries of the three existing PAs in the study region (Fig. 3). We named these proposed PAs as Yumsedong PA, Lachen PA and Chungthang PA after the respective prominent river valleys. These three proposed PAs cover a geographical area of 732 sq. km and would be primarily located in the North Sikkim district (Fig. 3; Table 1). The results also pointed to the need of expanding existing conservation boundaries of Maenam Wildlife Sanctuary, Fambong Lho Wildlife Sanctuary and Barsey (Rhododendron) Wildlife Sanctuary, primarily towards higher elevations in the north (Fig. 3). An additional geographical area of 164 sq. km needs to be set aside and added to the

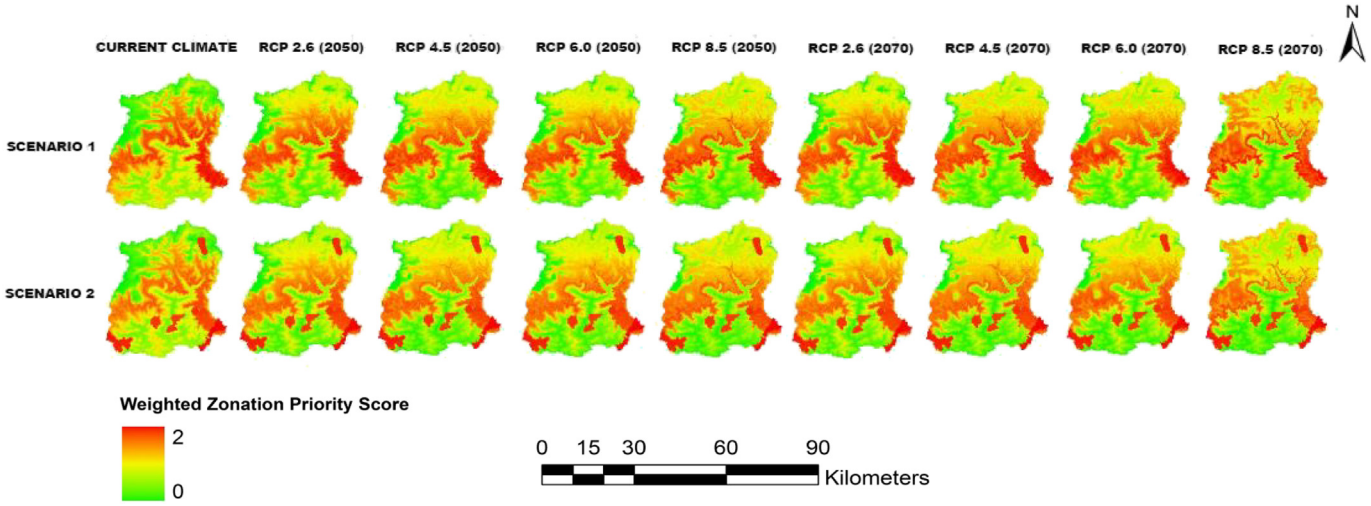


Fig. 2. Weighted Zonation priority scores of different areas in Sikkim Himalaya for conservation of 584 endemic plant species in present and future climate conditions (2050s, 2070s). RCPs represent various representative concentration pathways according to IPCC Fifth Assessment Report for each future climate condition, while Scenario 1 and 2 represents different runs of Zonation (Scenario 1 = Zonation analyses without including existing PA network of the Sikkim Himalaya; Scenario 2 = Zonation analyses with including existing PA network of the Sikkim Himalaya).

existing boundaries of these three reserves (see Table 1). Thus, we propose to demarcate an additional geographical area of 896 sq. km besides the existing PA coverage of 2183 sq. km for effective conservation of endemic plant species for the current and future climate conditions in the Sikkim Himalayan region.

The results of conservation efficiency analyses indicate that large PAs were more efficient in conserving endemic species under future climate change conditions than the small PAs. Khangchendzonga National Park with a total geographic area of 1784 sq. km had 1.16–1.24 times more top ranked 25% landscape cells in 2050s (PO = 44%) and 2070s (PO = 47%), respectively compared to the current climate scenario (PO = 38%) (Fig. 4). Likewise, the second largest PA in the study area, Pangolakha Wildlife Sanctuary (128 sq. km) showed increased conservation efficiency from 8% under the current climate conditions to 9% in 2050s and to 10% in 2070s, respectively (Fig. 4). However, the third largest PA, Barsey (Rhododendron) Wildlife Sanctuary (104 sq. km) showed same conservation efficiency under the current and future climate conditions. The smaller PAs such as Maenam Wildlife Sanctuary (35.34 sq. km) and Fambong Lho Wildlife Sanctuary (51.76 sq. km) showed no change in conservation efficiency between current and future climates (Fig. 4). Kyongnosla Alpine Wildlife Sanctuary with a total geographical area of 31 sq. km is likely to conserve 1% less priority conservation areas in future climate scenarios (PO = 2%) than the current climate (PO = 1%). Shingba (Rhododendron) Wildlife Sanctuary (43 sq. km) was found to be the worst affected PA in terms of conservation efficiency in the Sikkim

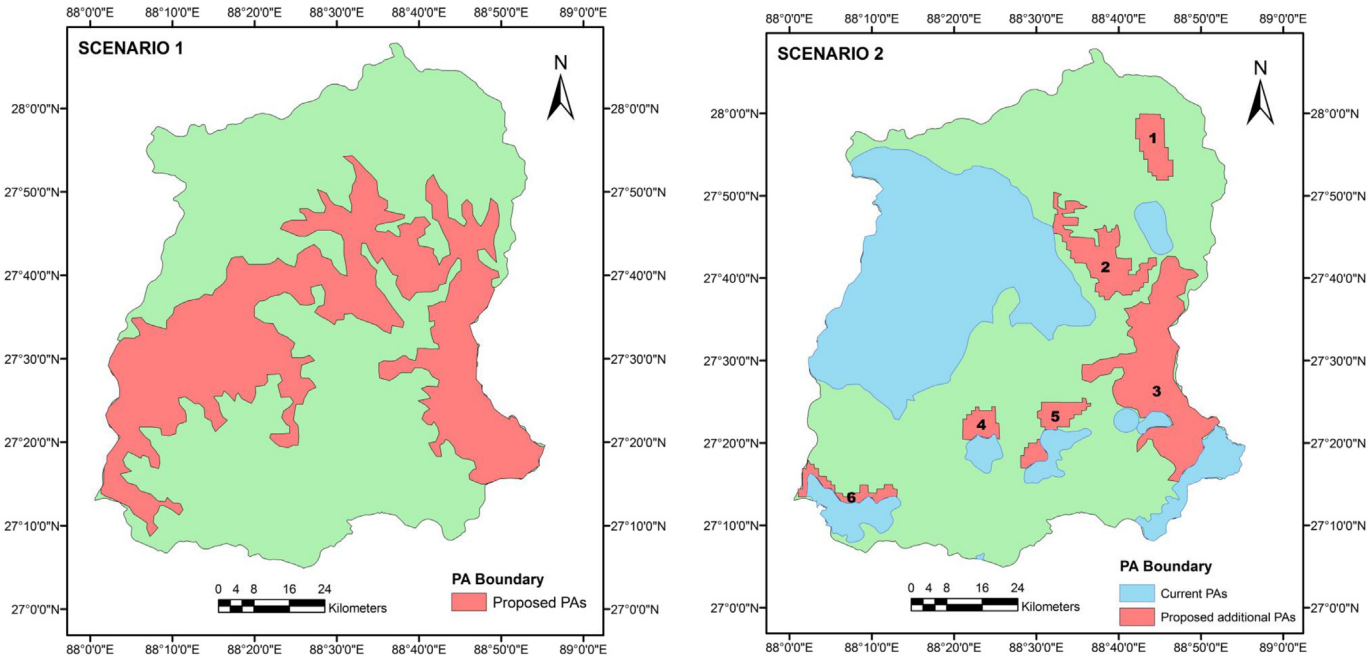


Fig. 3. Proposed locations of new PAs and extension of existing PA boundaries in Sikkim Himalaya that take into account Zonation priority scores across all climate conditions (current, 2050s, 2070s). The notations in the right panel of the figure represent the names of new proposed PAs: 1- Yumsedong Protected Area; 2 - Lachen Protected Area; 3 - Chungthang Protected Area; 4 - Maenam Wildlife Sanctuary (extension of existing PA boundary); 5 - Fambong Lho Wildlife Sanctuary (extension of existing PA boundary); 6 - Barsey Rhododendron Sanctuary (extension of existing PA boundary).

Table 1
Spatial spread and major areas encompassing the proposed new PAs in the Sikkim Himalayan region.

Sl. No.	Name of the proposed PA	Area (sq.km)	District	Major areas lying within proposed PA	Lat (North)	Long (East)
1	Yumsedong Protected Area	75.76	North	Yumsedong, Yumthang Valley	27.83° to 28.00°	88.69° to 88.78°
2	Lachen Protected Area	177.8	North	Lachen Forest Block	27.62° to 27.84°	88.53° to 88.74°
3	Chungthang Protected Area	478.2	North and East	Lachung Forest Block Chungthang Forest Block Labi Village Kabi Forest Block Gnathang Valley	27.25° to 27.84°	88.53° to 88.87°
4	Maenam Wildlife Sanctuary (extension)	46.73	South	Phamthang Village	27.34° to 27.41°	88.35° to 88.43°
5	Fambong Lho Wildlife Sanctuary (extension)	68.57	North and East	Rongong Village Tumlong Village Nampong Village Rakdong Village Tintek Village Tangyek Village Ramthang Village Patuk Village Chadey Village Lingzey Village	27.28° to 27.42°	88.47° to 88.61°
6	Barsey (Rhododendron) Wildlife Sanctuary (extension)	48.73	West	Sangkhu Village Hee-Patal Village	27.21° to 27.30°	88.02° to 88.22°

Sl. Nos. 1–3 represents areas to be included in fresh new PAs while Sl. Nos. 4–6 indicates areas to be included within already existing PA networks.

Himalayan region with merely 0.25% and 0.15% of top ranking 25% landscape cells in 2050s and 2070s, respectively as compared to the present 3% (Fig. 4). The smallest PA in the study region, Kitam Wildlife Sanctuary (6 sq. km), did not contain any area in top 25% of Zonation priority landscapes in either the current or future climate condition or RCP scenarios (Fig. 4).

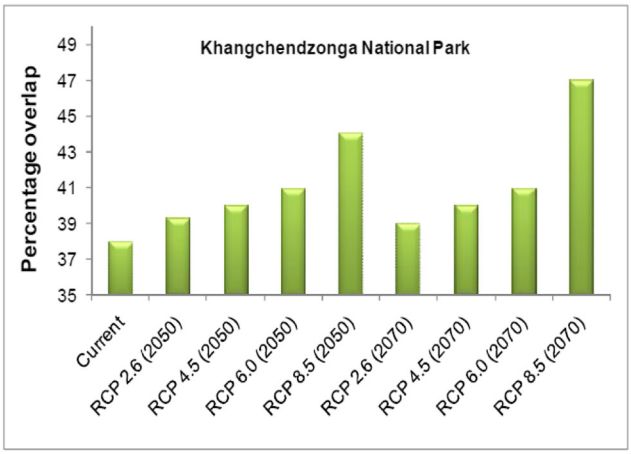
4. Discussion

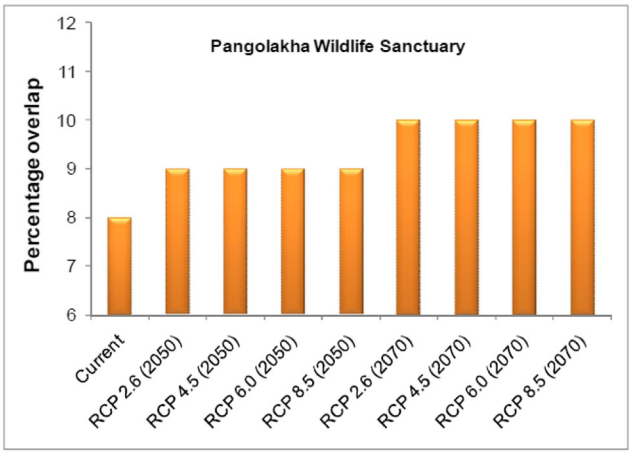
In the present study, we used MaxEnt modelling to project shifts in potential habitat areas for 584 endemic species from the present to the future climate scenarios (2050s, 2070s). All the model projections strongly suggested an upward northward shift in the potential habitats of nearly all the endemic species analysed (see research data linked to this article). Such species-specific responses to warming have already been documented in our earlier studies (Telwala et al., 2013; Manish et al., 2016). All these results indicate the vulnerability of the Himalayan plant species and communities to the ensuing climate change in the region. The present study can therefore assist the policy makers in making informed choices regarding mitigation and management of climate change impacts and to achieve conservation goals in a simple and swift manner.

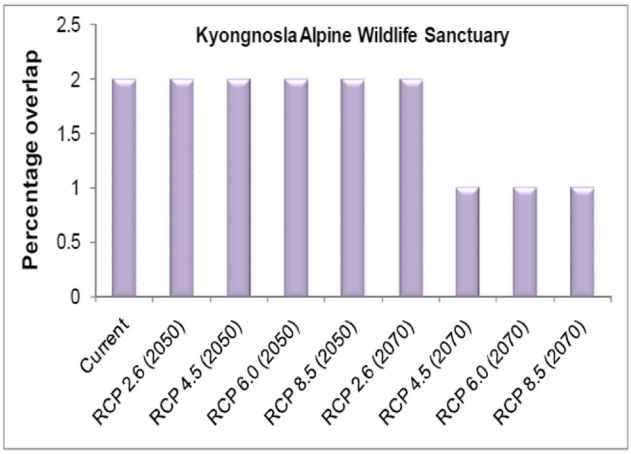
The results of the present study suggest that despite the relatively wide geographic coverage of PA network in Sikkim (~ 31%), the existing PA network does not conserve the regions of maximum plant diversity either under the current or the future climate scenarios (2050s, 2070s). The existing PA network in Sikkim was found to be protecting merely 36% of the high conservation value areas. Numerous researches have shown that often, most species rich areas are totally missed by the existing PA networks (Chape et al., 2005; Gruber et al., 2012; Thuiller et al., 2015). Jenkins and Joppa (2009) pointed out that of the total PA networks worldwide, only 5.8% provide adequate protection to biodiversity. Two major reasons cited commonly in literature for the inadequacy of PAs in meeting their conservation targets are: (i) PAs have traditionally been demarcated by the policy planners on the basis of non-systematic and limited data sets besides lack of quantitative site selection criteria (Margules and Pressey, 2000; Gaston et al., 2008; Culmsee et al., 2014; Kati et al., 2015), and (ii) PAs have often been established in view of aesthetics and visitor opportunities/experiences with focus on conservation of a single charismatic species (Margules and Pressey, 2000). Even in our study area, Shingba and Barsey Wildlife Sanctuaries are mandated primarily for the conservation of Rhododendrons. However, an objective analysis of empirical data revealed that these two PAs did not represent top conservation value areas. For example, Barsey (Rhododendron) Wildlife Sanctuary conserves only 8% of top conservation value areas under both current and future climate conditions, while Shingba (Rhododendron) Wildlife Sanctuary conserves only 3% and 0.15% of top conservation value areas in current and future climates, respectively (Fig. 4). These results highlight the need for a multi-taxon approach in defining areas of high conservation significance instead of a single-taxon charismatic species approach. One way of achieving a better conservation objective is to first evaluate the candidate conservation sites for cross-taxon diversity before formally designating them as PAs (Howard et al., 1998; Lund and Rahbek, 2002).

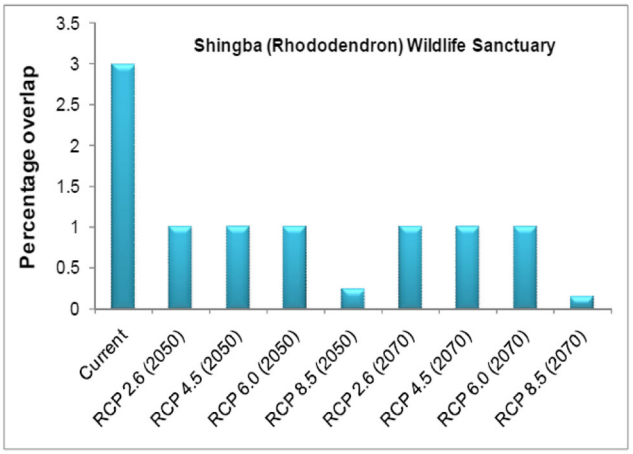
Based on the present results, we suggest that the coverage of PA network in Sikkim Himalaya should increase to 43% of the state's geographic area (with the proposed additional geographic area of 896 sq. km) to offset the negative impacts of on-going climate change in the region. This includes designation of three more potential areas as new PAs in the region, i.e. areas around Yumsedong, Lachen, and Chungthang. These areas merit PA status for their rich endemic biodiversity and for harbouring numerous pristine ecosystems (CISMHE, 2007). These areas also represent 'type localities' of many plant taxa and are the only known habitats of numerous rare and endemic species in the Himalayan region (see Pandit, 2017). For example, the first holotype of *Rhododendron glaucophyllum* was recorded from Lachen valley (3300 m) by J. D. Hooker in 1849. Likewise, *R. aeruginosum* (= *R. campanulatum* subsp. *aeruginosum*) was first reported by Hooker (1849) from Lachen and Lachung valleys. *R. sikkimense*, a rare and newly discovered species has been reported only from Yumthang valley (Pradhan and Lachungpa, 1990). These regions, therefore, have great evolutionary and conservation significance and loss of such habitats for lack of protective regulations would amount to huge disservice to the cause of conservation (Manish, 2017; Manish and Pandit, 2018b).

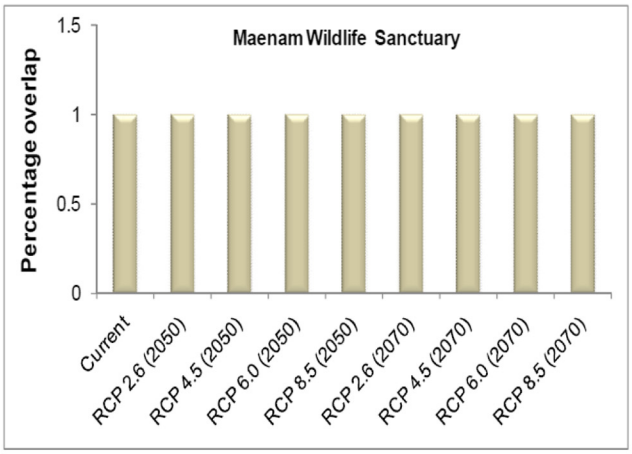
The other significant finding of this study relates to the relative usefulness of establishing a single large PA instead of several smaller PAs for effective biodiversity conservation (Cantú-Salazar and Gaston, 2010; Di Minin et al., 2013). Our investigations suggest that larger PAs have better chances of conserving areas with top conservation value under future climate scenarios. Here, we show that the largest PAs encompass a myriad of heterogeneous habitats from temperate to alpine ecosystems, therefore contain more diversity of unique taxa. For example, Khangchendzonga National Park extends from 1450 to

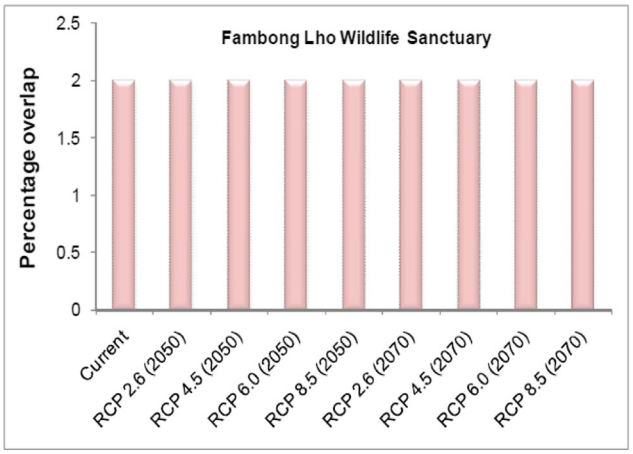












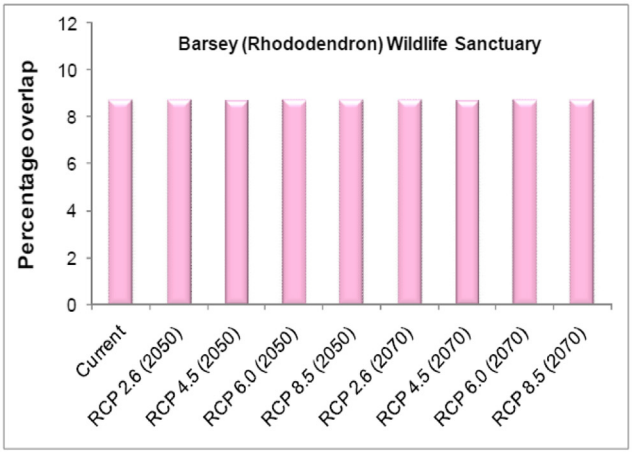


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Fig. 4. Proportion of the top 25% Zonation ranked landscapes conserved by existing PA network in the Sikkim Himalayan region in current and future climate conditions. RCPs represent various representative concentration pathways according to IPCC Fifth Assessment Report for each future climate condition.

7800 m, while Pangolakha Wildlife Sanctuary covers habitats extending from 1600 to 4400 m. The broad elevational extents and habitat diversity of these PAs allows them to efficiently buffer the effects of climate change because the maximum upward shift of species range margins in the region has been reported to be in the range of 23–998 m (Telwala et al., 2013; Manish et al., 2016). So, even in the likely event of species' ranges shift northwards at higher elevations, it is more likely that the larger PAs in the region would provide adequate space to the migrating plant taxa. Moreover, the two largest PAs in the study area (Khangchendzonga National Park and Pangolakha Wildlife Sanctuary) also cover elevations between 3500 and 4500 m, which harbour the highest endemic species richness (Manish et al., 2017). None of the other PAs except Shingba (Rhododendron) Wildlife Sanctuary have such an elevational spread. Thus, establishment of a larger PA instead of several small PAs shall be helpful in better utilization of limited resources available for conservation.

Some researchers have argued for creation of 'dynamic (floating)' PAs that can track species distributions as a better conservation strategy (Angelstam et al., 2004; Oetting et al., 2006; Rayfield et al., 2008). Such a strategy involves delimiting PAs based on fixed conservation targets and periodically re-evaluating and re-drawing their limits in response to natural and human-induced changes such as climate, fire, logging, etc. (see Rayfield et al., 2008). However, it is practically difficult to have such dynamic PAs in the Himalaya or elsewhere as a response to the climate change mitigation because of three major reasons: (i) Each species may have a unique response to the aforementioned changes including temperature and precipitation (Manish et al., 2016), (ii) Once notified, PAs are rarely declassified (Mascia and Pailler, 2011), and (iii) Redesigning PAs every now and then based on tracking species' range distributions would be practically impossible and a logistic nightmare for conservation managers. In the context of the Himalaya, a more effective strategy would be to broaden the existing boundaries or establish new PAs using a sound conservation significance analysis.

5. Conclusion

The results of the present study suggest that the current PA network in the Sikkim Himalayan region is inadequate to conserve its endemic plant diversity and the conditions are expected to deteriorate further under future climate scenarios due to loss of species habitats and shifting of species and community distribution ranges. Further, the high elevation regions and upper reaches of Sikkim Himalaya are top priority areas for conservation. The lowest ranked conservation areas are mostly found at lower elevations, close to the urban landscapes and human habitations. It would also be more prudent to design a single large PA with wide geographical and elevational extents instead of several small Pas; the large PA is likely to better buffer the effects of elevational range shifts in species and community distributions as a result of climate change. This study provides a rationale for the need to expand the current PA boundaries and re-design new ones in the Himalaya as urgently as we can.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2019.02.036.

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